THE COMPANY OF **Biologists**

RESEARCH ARTICLE

STEM CELLS AND REGENERATION

Location of transient ectodermal progenitor potential in mouse development

Lingyu Li[1,*], Chang Liu[2], Steffen Biechele[1,3,‡], Qingqing Zhu[2], Lu Song[2], Fredrik Lanner[1,§], Naihe Jing[2] and Janet Rossant[1,3,¶]

ABSTRACT

Ectoderm is one of the three classic germ layers in the early mouse embryo, with the capacity to develop into both the central nervous system and epidermis. Because it is a transient phase of development with few molecular markers, the early ectoderm is the least understood germ layer in mouse embryonic development. In this work, we studied the differentiation potential of isolated ectoderm tissue in response to BMP signaling at various developmental stages (E6.5, E7.0 and E7.5), and identified a transient region in the anterior-proximal side of the embryo at E7.0 that possesses the ability to become neural or epidermal ectoderm in response to the absence or presence of BMP4, respectively. Furthermore, we demonstrated that inhibition of Nodal signaling could direct the pluripotent E6.5 epiblast cells towards ectoderm lineages during differentiation in explants *in vitro*. Our work not only improves our understanding of ectodermal layer development in early embryos, but also provides a framework for regenerative differentiation towards ectodermal tissues.

KEY WORDS: Ectoderm, BMP4, Epidermis, Nodal

INTRODUCTION

During early vertebrate development, initially pluripotent cells become progressively restricted in their developmental choices. Central to this transition is the process of gastrulation, during which the epiblast develops into the three primary germ layers (Tam and Loebel, 2007). In mouse embryos, the epiblast at embryonic day (E) 5.5 is pluripotent, and epiblast stem cells (EpiSCs) can be derived from this stage of development (Brons et al., 2007; Tesar et al., 2007). At E6.5, gastrulation is initiated with the formation of the primitive streak on the posterior side of the embryo. Epiblast cells that ingress through the primitive streak form the mesoderm and the endoderm. The cells that do not pass through the primitive streak and remain on the anterior side of the epiblast form the ectoderm (Lu et al., 2001; Tam and Loebel, 2007).

[1]Program in Developmental and Stem Cell Biology, Hospital for Sick Children Research Institute, 555 University Avenue, Toronto, ON M5G 1X8, Canada. [2]State Key Laboratory of Cell Biology, Institute of Biochemistry and Cell Biology, Shanghai Institutes for Biological Sciences, Chinese Academy of Sciences, 320 Yue Yang Road, Shanghai 200031, China. [3]Department of Molecular Genetics, University of Toronto, Toronto, ON M5S 1A8, Canada.
*Present address: Department of Developmental Biology, Stanford University School of Medicine, Stanford, CA 94305, USA. ‡Present address: Eli and Edythe Broad Center of Regeneration Medicine and Stem Cell Research, Department of Obstetrics and Gynecology Center for Reproductive Sciences, University of California San Francisco, San Francisco, CA 94143, USA. §Present address: Department for Clinical Science, Intervention and Technology Division of Obstetrics and Gynecology, Karolinska Institutet Fertility Unit, Karolinska University Hospital, Huddinge K57, 14186 Stockholm, Sweden.

¶Author for correspondence (janet.rossant@sickkids.ca)

In *Xenopus*, the development of ectoderm proceeds through an ectodermal progenitor stage, which then differentiates to form the two major ectodermal lineages: surface ectoderm and neurectoderm (Hemmati-Brivanlou and Melton, 1997a; Hemmati-Brivanlou and Melton, 1997b; Wilson and Hemmati-Brivanlou, 1995). BMP4, a member of the transforming growth factor β (TGFβ) ligand superfamily, induces epidermal differentiation from the ectoderm. By contrast, suppression of bone morphogenetic protein (BMP) signaling, accomplished by BMP antagonists, leads to the specification of the neural ectoderm (Chang and Hemmati-Brivanlou, 1998; Wilson and Hemmati-Brivanlou, 1995).

In the mouse embryo, the pathways patterning the ectoderm have been less extensively studied. In early investigations, the fate map of the ectoderm was established using cell labeling and orthotopic and heterotopic grafts (Beddington, 1982; Beddington, 1981; Tam, 1989). At E6.5, the epiblast cells at the distal tip are fated to form neurectoderm, whereas the cells at the adjacent region anterior to the distal cap contribute to surface ectoderm. Other epiblast cells at E6.5 are multipotent and do not appear to be restricted to a single lineage outcome (Lawson et al., 1991; Quinlan et al., 1995). At E7.5, the proximal part of the ectodermal layer, which is close to the extra-embryonic ectoderm (ExE), is mostly restricted to becoming surface ectoderm. The remaining regions of the anterior ectodermal layer can be mapped into progenitor regions for forebrain, midbrain, hindbrain and spinal cord (Tam, 1989; Tam and Quinlan, 1996). Based on these fate-mapping studies, it remains unclear whether a transient ectodermal progenitor potential region exists in mouse embryo. Recently, Cajal and colleagues have discovered a small number of cells in mouse embryo that could contribute to both surface ectoderm and neural ectoderm during normal embryonic development. These cells were positioned between the proximal and distal regions of the anterior ectoderm layer at late gastrulation stage (Cajal et al., 2012). This would suggest that the majority of the ectoderm cells are biased to neural or epidermal fate except for this small subset of cells positioned in the narrow intermediate zone. However, it is important to note that in the intact embryo, cell fate regionalization does not necessarily indicate lineage commitment. Although local signals may lead to early separation of the surface ectoderm and neurectoderm cell fate in the intact embryo, these cells may retain a broader potential when explanted *in vitro* in response to new signals or the removal of repressive signals. For example, Osorno et al. revealed that presomitogenesis-stage embryo (E7.5-E8.0) tissue can also be cultured as pluripotent EpiSCs when explanted in activin/fibroblast growth factor (FGF) conditions (Osorno et al., 2012).

In this study, we isolated anterior ectodermal tissue from E6.5, E7.0 and E7.5 mouse embryos, and studied their differentiation potential by culturing these tissue fragments in chemically defined medium with or without BMP4. We found that, at E6.5, the anterior part of the mouse embryo still retained pluripotency, giving rise to

Development

all three germ layer derivatives. By E7.0, the anterior part of the ectodermal layer was no longer pluripotent but had the potential to become either epidermis or neurectoderm, depending on the presence or absence of BMP4, respectively. However, this is a very transient phase of development because by E7.5, the ectoderm was no longer responsive to BMP4 and was restricted to either neural or epidermal fate, depending on its position in the embryo.

In mouse embryos, Nodal signaling is important for primitive streak formation and mesoderm/endoderm development (Brennan et al., 2001; Conlon et al., 1994; Dunn et al., 2004; Zhou et al., 1993). The anterior visceral endoderm (AVE) produces the Nodal antagonists Lefty1 and cerberus 1 (Cer1) to block mesoderm formation in the anterior region and promote neural development (Perea-Gomez et al., 2001; Perea-Gomez et al., 2002; Thomas and Beddington, 1996). Mouse embryos deficient for the activity of Nodal fail to form mesoderm and definitive endoderm. When explanted and cultured *in vitro*, *Nodal*^{−/−} epiblast cells readily differentiate into neurons (Camus et al., 2006). Studies in mouse EpiSCs and human embryonic stem cells (ESCs) also revealed that inhibition of Nodal signaling by SB431542 (Inman et al., 2002; Laping et al., 2002) attenuates mesoderm/endoderm differentiation and promotes neural induction (Chng et al., 2010; Patani et al., 2009; Vallier et al., 2009). A recent study further revealed that cells developing from EpiSCs in the absence of extrinsic signals (including Nodal signaling) express levels of core transcription factors similar to the anterior neural plate of ~E7.5 embryos (Iwafuchi-Doi et al., 2012). We show here that Nodal inhibition is not merely an enhancer of neural fate. The addition of Nodal inhibitor promotes ectodermal progenitor potential from the pluripotent anterior regions of E6.5 embryos. We propose that attenuation of Nodal signaling during mouse gastrulation promotes the initial formation of ectoderm and that subsequent exposure to different levels of BMP signaling determines the regional commitment to neural or epidermal fate.

RESULTS

Dynamic patterns of gene expression during ectoderm formation

During ectoderm formation, the loss of pluripotency and acquisition of specificity is a progressive, gradual process. In order to gain a detailed overview of the process, we examined gene expression patterns in mouse embryos from E6.0 to E7.5 using whole-mount *in situ* hybridization (Fig. 1).

The primitive streak marker *T* is expressed in the posterior side of the epiblast from E6.5 and gradually extends along the posterior edge to the distal point of the egg cylinder by E7.5 (Fig. 1A). The pluripotent marker *Pou5f1* (*Oct4*) is highly expressed in the whole epiblast until E7.5, from which stage it becomes weak in the anterior side (Fig. 1B). The expression of the epiblast marker *Fgf5* is reduced by E7.0 concurrent with the extension of the primitive streak (Fig. 1C). Although *Sox2* and *Oct6* (*Pou3f1*) are considered as neural markers after E7.5, they are initially expressed throughout the epiblast, but become restricted to the anterior side by E6.5 (Fig. 1D,E).

Other neurectoderm markers, *Six3* and *Hesx1* (Oliver et al., 1995; Thomas and Beddington, 1996), are not seen until E7.5. *Six3* is only detectable at E7.5 in the anterior part of the ectodermal layer (Fig. 1F). *Hesx1* is expressed in the AVE at E7.0, and later found in the anterior part of the ectodermal layer at E7.5 (Fig. 1G). Epidermal markers, the cytokeratins *Krt8* (*K8*) and *Krt18* (*K18*), were previously reported to be expressed in the single-layer ectodermal cells from E8.5 (Aberdam et al., 2007b). However, our data show
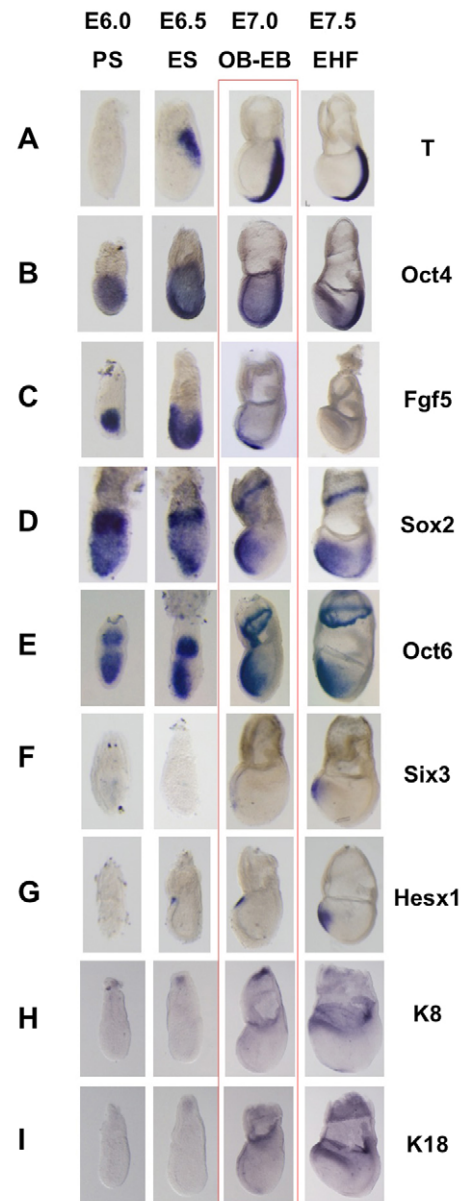

Fig. 1. Dynamic patterns of marker gene expression during ectoderm formation in mouse embryos. (A) *T* is expressed in the posterior side from E6.5. (B) *Oct4* is reduced in the anterior side by E7.5. (C) *Fgf5* expression is reduced in the epiblast by E7.0. (D,E) *Sox2* and *Oct6* are initially expressed in the epiblast and ExE, before being restricted to the anterior side from E6.5. (F) *Six3* is expressed in the anterior region at E7.5. (G) *Hesx1* is expressed in the AVE at E7.0, and then later also in the anterior ectoderm at E7.5. (H,I) *K8* and *K18* are expressed in the anterior region at E7.5. All are lateral views, with the anterior to the left. The red rectangle is used to highlight the E7.0 results.

that *K8* and *K18* expression is detectable in the anterior side as early as E7.5 (Fig. 1H,I). Notably, the *K8*- and *K18*-positive region is more proximal than the *Six3*- and *Hesx1*-positive region.

Our results show that the early epiblast marker *Fgf5* is downregulated by E7.0, but the neural markers *Six3* and *Hesx1* and the epidermal markers *K8* and *K18* are not yet expressed at this stage. This raises the possibility that an intermediate stage is present at E7.0, when cells can develop into either neural or epidermis depending on the cells' environment.

Explant cultures demonstrate progressive specification of ectoderm lineages from E6.5 to E7.5

To test the differentiation potential of the ectoderm at different developmental stages, we collected anterior ectoderm tissues at three time points: E6.5, E7.0 and E7.5. Reverse transcription quantitative PCR (RT-qPCR) analyses were performed on the explants to assess the purity of the dissected ectodermal tissue. Minimal contamination from non-ectodermal tissues was observed (supplementary material Fig. S1). Given the differences in gene expression profiles of the anterior ($Sox2^+$; $Oct6^+$) and posterior (T^+) halves, we bisected the ectoderm layer into anterior and posterior portions, and cultured them as explants in order to compare variations in their developmental potential.

The epiblast tissue at E6.5 is not committed to ectoderm

The epiblast tissue was dissected away from the overlying visceral endoderm and ExE at E6.5, and then cut into anterior and posterior portions (Fig. 2A). Gene expression profiling showed that the epiblast tissue did not express the trophectoderm marker $Cdx2$ (supplementary material Fig. S1Aa), but expressed the epiblast marker $Fgf5$ in both anterior and posterior portions (supplementary material Fig. S1Ab). High expression of T in the posterior portion (supplementary material Fig. S1Ac) and enrichment for $Oct6$ and $Sox2$ in the anterior portion (supplementary material Fig. S1Ad,Ae) was also observed, complementing our *in situ* hybridization results.

During the 5-day culture, both anterior and posterior explants showed formation of stratified cells in BMP4-supplemented medium

that was not observed in controls (Fig. 2B). Time course experiments showed that $Oct4$ was downregulated rapidly in both anterior and posterior explants, regardless of BMP4 supplementation (supplementary material Fig. S2A). The primitive streak marker T was transiently upregulated in anterior explants in both control and BMP4 conditions on day 1, and remained high in posterior explants. From day 3, T expression was sharply downregulated in all explants to barely detectable levels by day 5 (supplementary material Fig. S2B). The neural marker $Sox1$ was upregulated only in anterior and posterior explants cultured without BMP4 (supplementary material Fig. S2C). By contrast, the epidermal marker $K18$ and mesoderm marker $Flk1$ (Kdr) were only upregulated in explants cultured with BMP4 (supplementary material Fig. S2D,E).

We assessed additional marker expression in anterior and posterior explants at day 5 of culture. In the absence of BMP4, the explants expressed the neural markers $Sox1$ and $Pax6$ (Fig. 2Ca,Cb). Intriguingly, their expression levels were higher in the anterior explants compared with the posterior, suggesting that there is already some restriction in potential towards a neural fate in the anterior versus posterior explants. However, in the presence of BMP4, both anterior and posterior explants expressed the epidermal markers $K18$ and $Krt14$ ($K14$) (Kirfel et al., 2003; Moll et al., 1982) (Fig. 2Cc,Cd), and the mesoderm/endoderm markers $Flk1$ and $Gata6$ (Fig. 2Ce-Cf), suggesting that the epiblast retains the capacity to respond to BMP4 and induce surface ectoderm and mesoderm/endoderm gene expression.

Explant culture of proximal and distal epiblast explants (supplementary material Fig. S2F) also showed equivalent induction
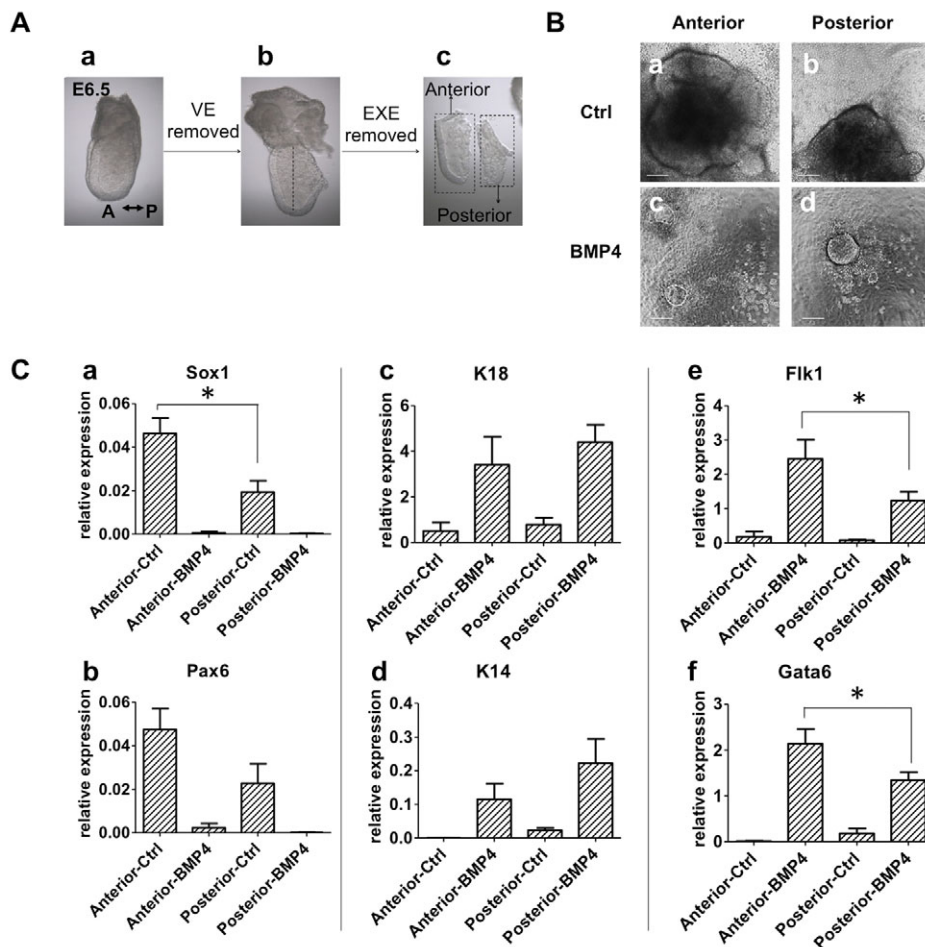

Fig. 2. The anterior part of the embryonic ectoderm at E6.5 is pluripotent.
(A) Dissection process of E6.5 mouse embryos. (B) Morphology of explants cultured in control (Ctrl; Ba,Bb) and BMP4-supplemented (Bc,Bd) medium. Scale bar: 100 μm. (C) RT-qPCR analysis of marker gene expression of anterior and posterior explants cultured in control or BMP4-supplemented medium. *n*=4 biological replicates. *$P<0.05$. Error bars represent s.d.

of mesoderm/endoderm markers in the presence of BMP4
(supplementary material Fig. S2G).

The data described above indicate that the epiblast at E6.5 has the
ability to give rise to neural, epidermal and mesoderm/endoderm
cells, and implies that the ectodermal germ layer restriction has not
yet occurred in the epiblast at E6.5.

The anterior part of the E7.0 ectodermal layer has ectoderm but not mesoderm/endoderm potential in the presence of BMP4

In the E7.0 mouse embryo, embryonic tissue was first dissected into
anterior and posterior portions (Fig. 3Aa,Ab). Mesoderm, endoderm
and ExE were subsequently removed to generate anterior and
posterior ectodermal explants (Fig. 3Ac,Ad). As expected, the
ectoderm explants do not express cerberus 1 (*Cer1*), which is
selectively expressed in the anterior visceral endoderm, or *Hex*
(*Hhex*), which is found in the anterior definitive endoderm (Thomas
et al., 1998) (supplementary material Fig. S1Ba,Bb). Consistent with

a previous study (Yamaguchi et al., 1993), the mesoderm marker
Flk1, which is enriched in the anterior mesoderm at E7.0, was not
detected in either anterior or posterior ectodermal fragments
(supplementary material Fig. S1Bc). The primitive streak marker *T*
was highly expressed in the posterior fragments but not in the
anterior (supplementary material Fig. S1Bd). *Oct6* and *Sox2* were
still enriched in the anterior fragments (supplementary material
Fig. S1Be,Bf).

After 5 days of culture, we found that the anterior explants
showed a homogeneous paving-stone-like morphology in BMP4-
supplemented medium (Fig. 3B). Elevated expression of the neural
markers *Sox2*, *Sox1*, *Pax6* and *Six3* were observed in the anterior
explants cultured without BMP4 (Fig. 3Ca). By contrast, in the
presence of BMP4, the expression of these neural markers was not
found. Rather, epidermal markers such as *K8*, *K18*, *Krt5* (*K5*),
K14, *Krt15* (*K15*) and *ΔNp63* (Aberdam et al., 2007a; Kirfel et al.,
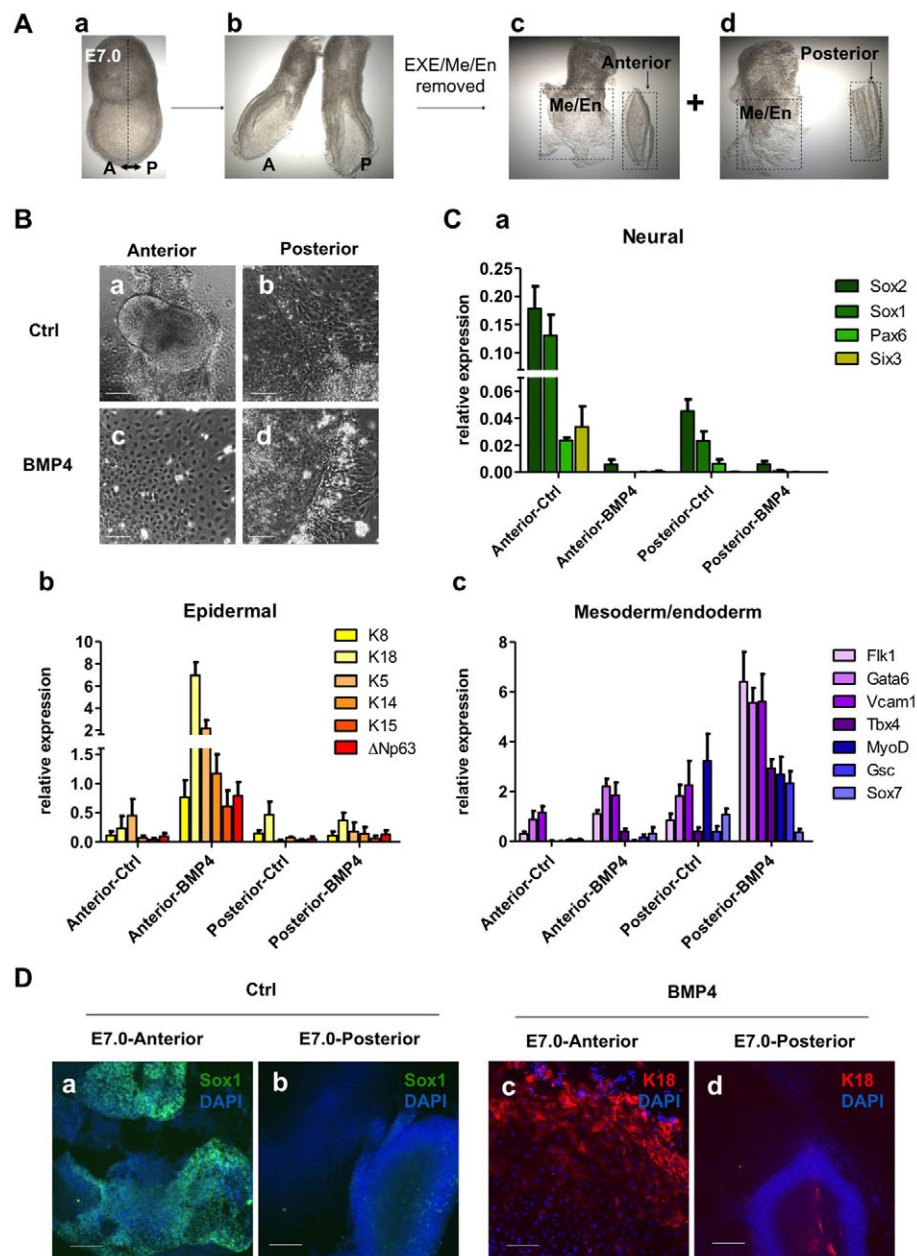2003; Moll et al., 1982; Troy et al., 2011) (Fig. 3Cb) were

Fig. 3. The anterior ectoderm in E7.0 mouse embryo has the potential to give rise to neural and epidermal cells. (A) Dissection process of E7.0 mouse embryos. (B) Morphology of explants cultured in control (Ctrl; Ba,Bb) and BMP4-supplemented (Bc,Bd) medium. (C) RT-qPCR analysis of marker gene expression of anterior and posterior explants cultured in control or BMP4-supplemented medium. *n*=6 biological replicates. Error bars represent s.d. (D) Immunostaining for Sox1 and K18 in anterior and posterior explants cultured without (Ctrl) or with BMP4. Scale bars: 100 μm.

observed. Very low levels of mesoderm/endoderm markers, such as *Flk1*, *Gata6*, *Vcam1*, *Tbx4*, *MyoD* (*Myod1*), *Gsc* and *Sox*7, were expressed (Fig. 3Cc). These results suggests that the anterior ectoderm tissue of E7.0 mouse embryo has the potential to become either neural or epidermal lineage, and is restricted to an ectodermal fate.

The posterior explants expressed lower levels of neural markers in control medium (Fig. 3Ca), and failed to express epidermal markers in BMP4-supplemented medium (Fig. 3Cb). However, high levels of mesoderm/endoderm markers were found in response to BMP4 (Fig. 3Cc) suggesting that the posterior portion of the E7.0 ectodermal layer preferentially responds to BMP4 by forming mesoderm/endoderm. Immunostaining confirmed the expression of K18 (epidermal) and Sox1 (neural) markers in most cells in the anterior explants (with or without BMP4, respectively). Only a few cells in the posterior explants expressed these markers (Fig. 3D).

In order to expose transient changes that might be obscured by the 5-day culture regimen, we analyzed a more detailed time course of changes in the expression of some important genes. The expression of *T* and the early mesoderm/endoderm marker *Mixl1* (Hart et al., 2002) were never activated in anterior explants during the 5-day culture period regardless of BMP4 supplementation. The higher expression level in the posterior explants was rapidly downregulated after the first day (supplementary material Fig. S3A,B). In the absence of BMP4, the neuronal markers *Sox2* and *Sox1* were upregulated in anterior explants. An initial transient increase in these markers was observed in posterior explants but the levels were lower than their anterior counterparts (supplementary material Fig. S3C,D). With supplementation of BMP4, *K18* was obviously activated from day 3 in anterior explants (supplementary material Fig. S3E), whereas *Flk1*, *Gata6* and the endoderm marker *Gsc* (Yasunaga et al., 2005) were highly activated only in posterior explants (supplementary material Fig. S3F-H).

In summary, our results suggest that the anterior part of the ectodermal layer becomes restricted to ectodermal progenitor potential by E7.0 with the ability to further differentiate into either neural or epidermal tissue in response to BMP4.
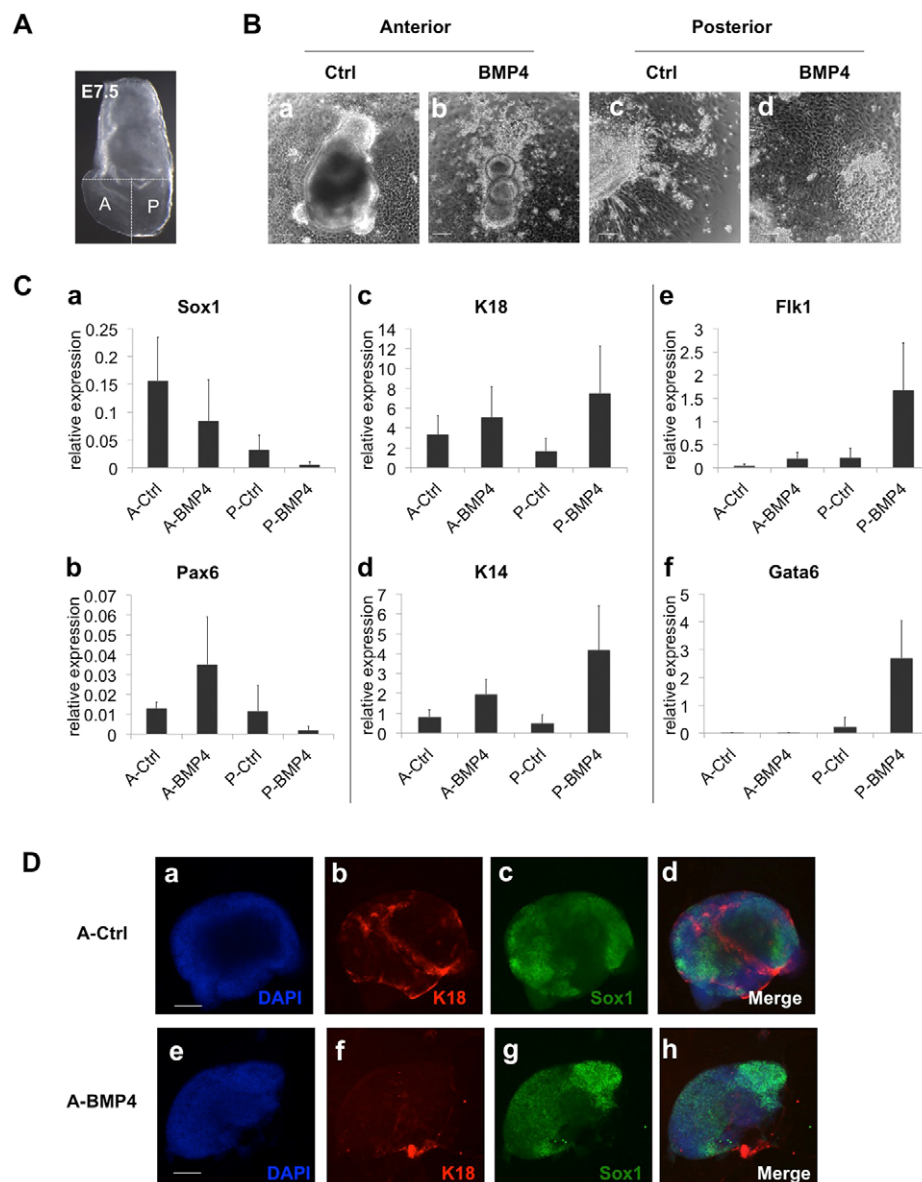

Fig. 4. BMP4 cannot repress neural induction or promote epidermal fate in the anterior ectoderm at E7.5. (A) Morphology of an E7.5 mouse embryo. Dotted line indicates position of dissection. (B) Morphology of explants cultured in control (Ctrl; Ba,Bc) and BMP4-supplemented (Bb,Bd) medium. (C) RT-qPCR analysis of marker gene expression of anterior explants (A-Ctrl, A-BMP4) and posterior explants (P-Ctrl, P-BMP4) cultured in control or BMP4-supplemented medium. *n*=4 biological replicates. Error bars represent s.d. (D) Immunostaining of Sox1 and K18 in anterior explants cultured in control (Da-Dd) and BMP4-supplemented (De-Dh) medium. Scale bars: 100 μm.

Surface ectoderm and neural ectoderm are committed by E7.5

It is widely accepted that the neural plate has already formed by E7.5, which is supported by *in situ* hybridization of *Hesx1* and *Six3* in the anterior ectoderm at this developmental time point (Fig. 1E,F). We also observed expression of the epidermal markers *K8* and *K18* in the more proximal region of the ectoderm (Fig. 1G,H), suggesting that the epidermal region might also be specified. To test our model, we separated the ectodermal layer of E7.5 embryos into anterior and posterior portions, and tested their differentiation potential in culture (Fig. 4A).

In contrast to E6.5 and E7.0 explants, we found that the addition of BMP4 in the media could not prevent the formation of neurectoderm outgrowths in the anterior explants of E7.5 embryos (Fig. 4Bb). RT-qPCR analysis also showed that BMP4 treatment did not cause a statistically significant difference in the expression of *Sox1*, *Pax6*, *K18* and *K14* in the anterior explants (Fig. 4Ca-Cd). The mesoderm/endoderm markers *Flk1* and *Gata6* were upregulated in the posterior, but not in the anterior, explants (Fig. 4Ce,Cf).

Immunostaining revealed the presence of two cell populations in the control anterior explants: Sox1-positive cells in neurectoderm aggregates (Fig. 4Dc), and K18-positive cells surrounding them (Fig. 4Db). Addition of BMP4 did not noticeably change the ratio of K18- or Sox1-positive cells in the anterior explants (Fig. 4Df,Dg). Previous reports have suggested that, rather than inhibiting neuronal formation at this stage, BMP4 directs the differentiation and specification of neural progenitors (Hendrickx et al., 2009; Moon et al., 2009; Shan et al., 2011). This is consistent with our results, as BMP4 did not eliminate neural marker expression but only altered their expression level. In summary, our work supports the notion that neural ectoderm is committed by E7.5 and also suggests that this is the time of the emergence of cells restricted to surface ectoderm.

BMP activity and refinement of the ectodermal progenitor region in E7.0 mouse embryo

BMP4 is expressed in the ExE from E6.5 to E7.5, and can presumably act at a distance in the associated epiblast to influence cell fate (Fig. 5Aa-Ac). The expression of the BMP4 direct targets *Id1* and *Id2* in the proximal region of the embryonic tissue from E7.0 (Fig. 5Ad-Ai) could define the boundaries of BMP4 activity. At E7.5, the proximal region of BMP signaling activity, as denoted by *Id1* and *Id2* expression, is coincident with the *K18*-positive region (Fig. 5Aj-Al), consistent with a role for BMP signaling in epidermis induction.

The differential downstream activity of BMP4 along the proximal-distal axis of the epiblast raises the possibility that the differentiation potential of anterior E7.0 ectodermal cells might be influenced by their proximity to the ExE. In order to test our hypothesis, we further dissected the anterior ectoderm into proximal (anterior/proximal, A/P) and distal (anterior/distal, A/D) portions (Fig. 5Ba). As expected, *Id1* and *Id2* are expressed at much higher levels in the A/P region compared with the A/D (Fig. 5Bb). After 5 days of culture, we found that both A/P and A/D explants expressed *Sox1*, *Pax6* and *Six3* in the absence of BMP4 (Fig. 5Ca). However, only A/P explants expressed the epidermal markers *K18*, *K14* and *K15* at high levels when cultured in the presence of BMP4 (Fig. 5Cb). Consistent with whole E7.0 anterior explants (Fig. 3Cc), both A/P and A/D expressed mesoderm/endoderm markers at lower levels compared with the posterior region (Fig. 5Cc). These results suggest that the A/P fragment possesses the potential to become both neurons and epidermis.
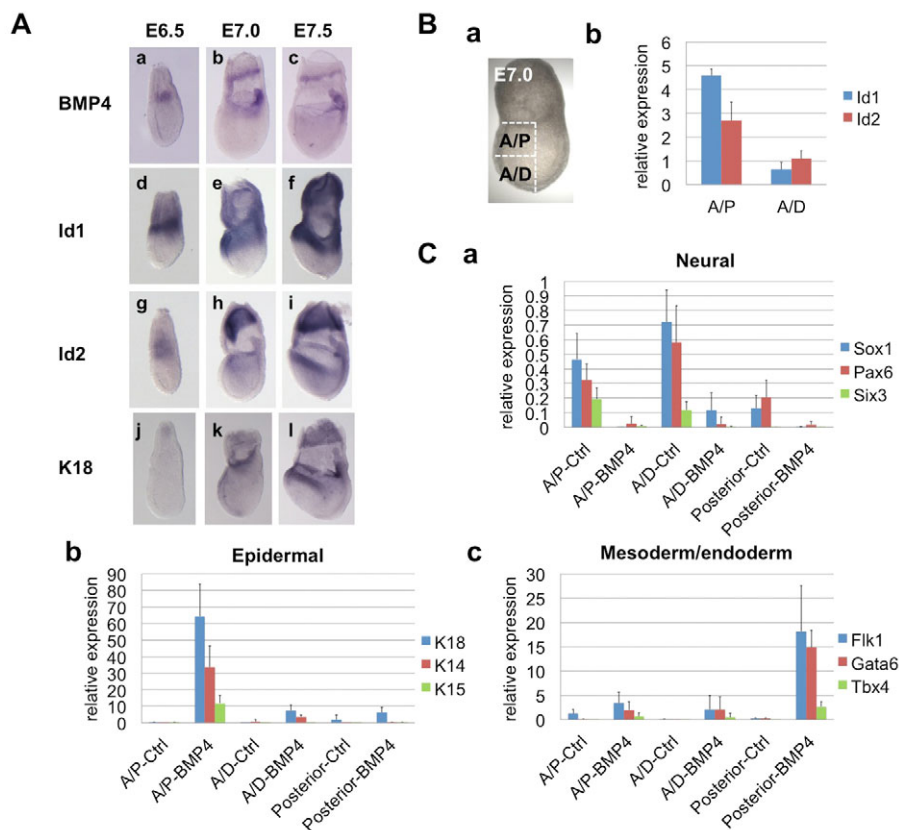

Fig. 5. The anterior/proximal (A/P) region of ectoderm at E7.0 has ectodermal progenitor potential. (A) Whole-mount *in situ* hybridization for *Bmp4*, *Id1*, *Id2* and *K18* in mouse embryos at E6.5, E7.0 and E7.5. (B) Separation of anterior ectoderm in E7.0 mouse embryo into proximal (anterior/proximal, A/P) and distal portions (anterior/distal, A/D) as indicated (Ba). *Id1* and *Id2* show different expression levels in A/P and A/D (Bb). (C) RT-qPCR analysis of neural marker genes *Sox1*, *Pax6* and *Six3* (Ca), epidermal marker genes *K18*, *K14* and *K15* (Cb), mesoderm/endoderm marker genes *Flk1*, *Gata6* and *Tbx4* (Cc) in A/P, A/D and posterior explants cultured in control or BMP4-supplemented medium. *n*=4 biological replicates. Error bars represent s.d.

To investigate the possibility of additional regional biases, we subdivided the A/P fragment into four smaller pieces (fragments 1, 2, 3 and 4) (Fig. 6Aa,Ba). Owing to the difficulty of culturing small ectoderm fragments in the chemically defined medium, we co-cultured these fragments with the much larger anterior ectoderm explants. Using mouse embryos ubiquitously expressing enhanced green fluorescent protein (EGFP) (Hadjantonakis et al., 1998), we isolated fragments 1, 2, 3 and 4 of the A/P region at E7.0 (Fig. 6Aa,Ab), aggregated each fragment with an anterior fragment from a wild-type E7.0 embryo (GFP negative), and co-cultured them in N2B27 with or without BMP4 for 5 days (Fig. 6Ac,Ad). We were able to obtain expansion of the GFP-positive cells within the aggregated populations.

We sorted out the GFP-positive cells derived from the small ectoderm fragments using fluorescence-activated cell sorting (FACS) and analyzed gene expression of various lineage markers. Three of the four fragments expressed similar levels of epidermal markers and neural markers when cultured with or without BMP4, respectively, with the exception of fragment 2, which expressed lower levels of epidermal markers (Fig. 6Bb,Bc). Consistent with the whole A/P explants (Fig. 5Cc), all four fragments expressed mesoderm/endoderm markers at much lower levels compared with the posterior explants (supplementary material Fig. S4). We conclude that, despite some heterogeneity in the differentiation efficiency of ectodermal derivatives, the entire A/P fragment can give rise to neural and surface ectoderm. By comparison, the small fragment of the A/D region co-cultured with large anterior ectoderm explant expressed very weak epidermal markers and relatively higher levels of mesoderm/endoderm markers when cultured with BMP4 (supplementary material Fig. S5). This result confirmed the difference between A/D and A/P regions. Moreover, it indicated that the large anterior fragment did not alter the differentiation potential of small fragments in an obvious manner.

Taken together, our data indicates that a proximal-distal BMP signaling gradient in the anterior ectoderm can influence its differentiation potential. The anterior/proximal region, which exhibits higher BMP activity, can give rise to neural and epidermal cells, whereas the anterior/distal region, which has lower BMP activity, preferentially generates neural tissues.

Derivation of the transient ectodermal progenitor stage by brief inhibition of Nodal signaling in E6.5 anterior epiblast

Given that Nodal antagonists are secreted from the AVE at E6.5-E7.0 to suppress Nodal activity at the anterior side (Perea-Gomez et al., 2001; Perea-Gomez et al., 2002; Thomas and Beddington, 1996), we hypothesized that Nodal inhibition probably directs the differentiation of epiblast cells towards ectodermal progenitor populations, which can then differentiate into neural or epidermal fate in the absence or presence of BMP4, respectively.

To verify this hypothesis, we tested the differentiation potential of E6.5 epiblast tissue pre-treated for 6 hours with the nodal inhibitor SB431542, prior to culturing the cells in our chemically defined media with or without BMP4. Consistent with previous reports (Camus et al., 2006), the epiblast tissue treated with Nodal inhibitor, regardless of anterior or posterior identity, expressed high levels of the neural markers *Sox1*, *Sox2*, *Pax6*, *Map2* and *Six3* after 5 days of differentiation in BMP4-negative medium, except that *Six3* was not expressed in the posterior portion (Fig. 7Aa,Ba). When cultured with BMP4, the anterior explants differentiated predominantly into epidermal-like cells, expressing very low levels of mesoderm/endoderm markers, and high levels of the epidermal markers *K8*, *K18*, *K5*, *K14*, *K15* and *ΔNp63* (Fig. 7Ab). This suggests that the E6.5 anterior tissue can be restricted to ectoderm by brief inhibition of Nodal signaling (Fig. 7C).

Surprisingly, Nodal inhibition had minimal effects on epidermal and mesoderm/endoderm marker expression in the posterior
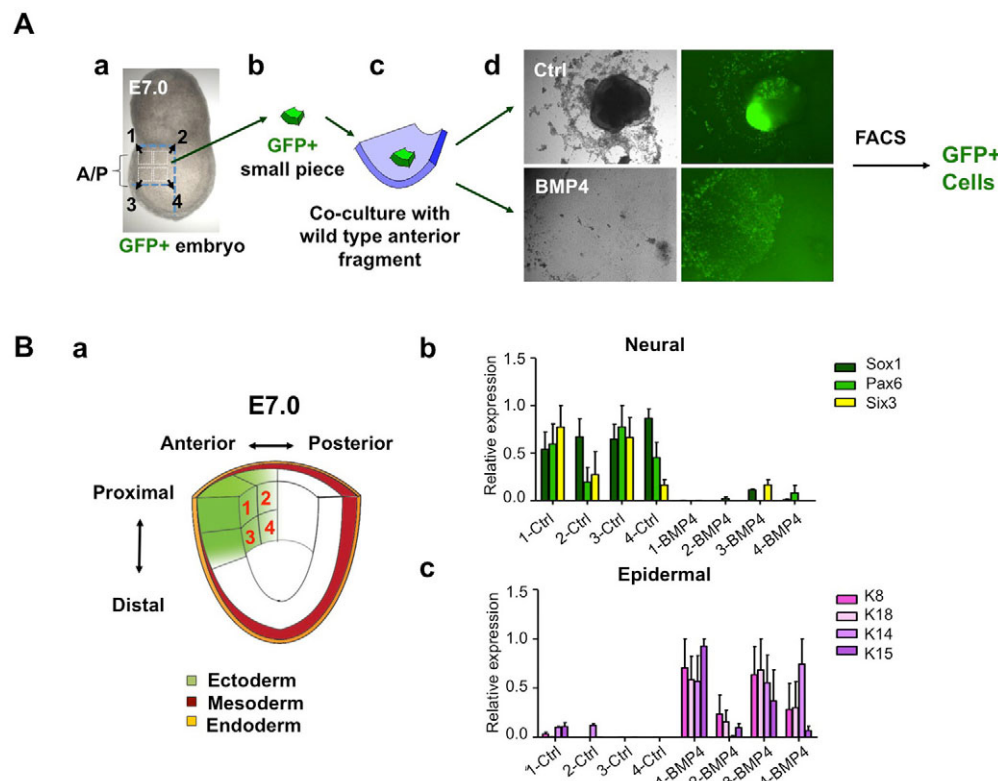

Fig. 6. Regionalization of ectodermal progenitor potential in E7.0 ectodermal layer in mouse. (A) Schematic of the co-culture method used to obtain derivatives from EGFP-positive A/P fragments 1, 2, 3 and 4. (B) Schematic illustrating locations of fragments 1, 2, 3 and 4 in A/P region (Ba). RT-qPCR analysis of neural (Bb) and epidermal (Bc) marker gene expression in derivatives of fragments 1, 2, 3 and 4 cultured in control (Ctrl) medium or BMP4-supplemented medium. *n*=4 biological replicates. Error bars represent s.d.
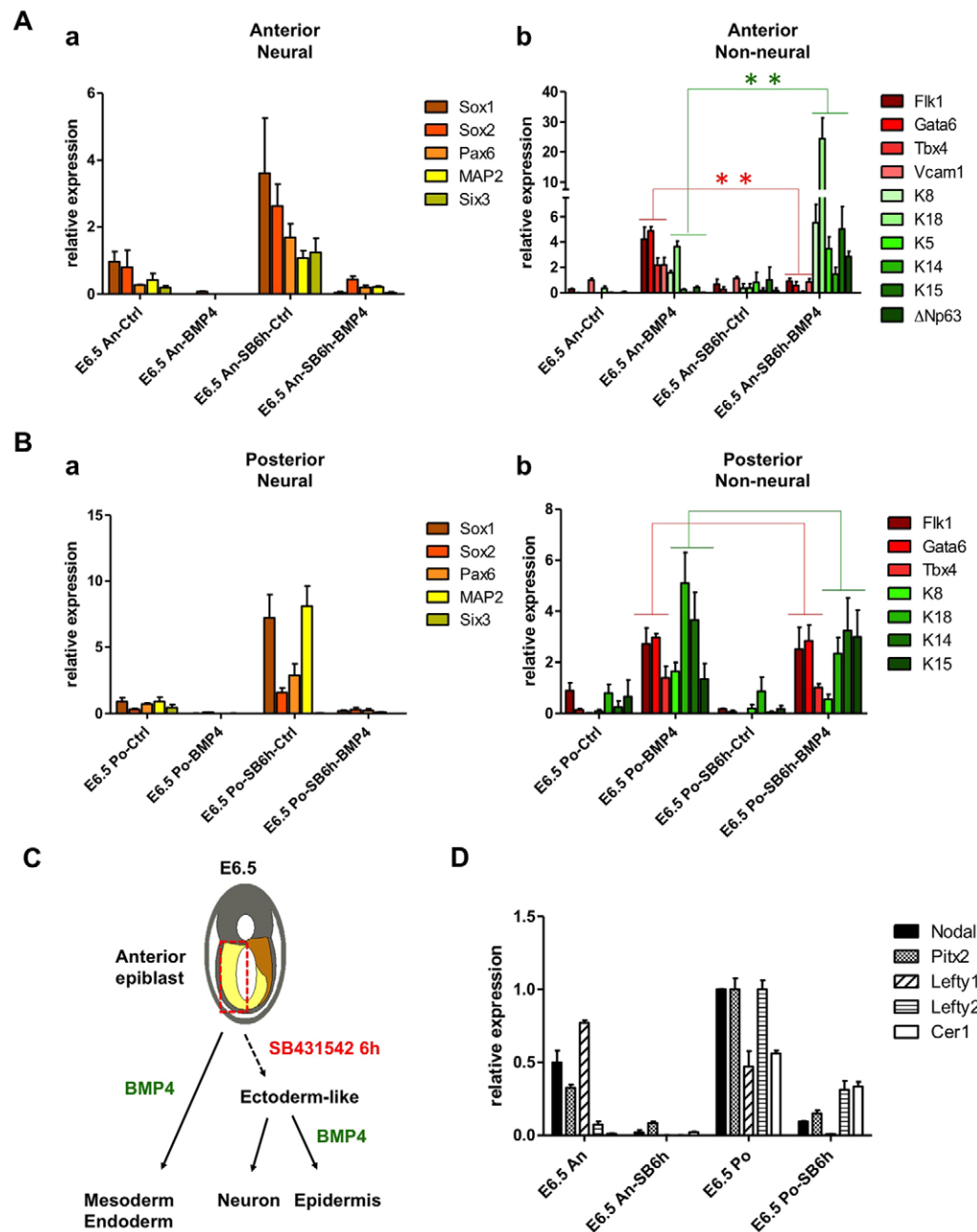
Fig. 7. Derivation of ectodermal progenitor-like cells by short-term inhibition of Nodal signaling.
(A) RT-qPCR analysis of marker gene expression in four groups of E6.5 mouse anterior explants that have differentiated for 5 days: the first group is cultured in N2B27 (E6.5 An-Ctrl), the second is cultured with BMP4 (E6.5 An-BMP4), the third and the fourth groups are pre-treated with SB431542 (10 μM) for 6 hours, and then differentiated separately in control medium (E6.5 An-SB6h-Ctrl) or medium supplemented with 10 ng/ml BMP4 (E6.5 An-SB6h-BMP4). Each group of data has four biological replicates. **$P<0.01$. (B) Marker gene expression in E6.5 posterior explants cultured as described in A. $n=4$ biological replicates. (C) Model of differentiation process in E6.5 anterior explants. Red rectangle indicates anterior epiblast. (D) RT-qPCR analysis of Nodal downstream targets in E6.5 anterior epiblast, posterior epiblast and explants cultured with SB431542 for 6 hours. Three embryos were collected for each group. Error bars represent s.d.

explants (Fig. 7Bb). In order to elucidate the molecular mechanisms underlying our observations, we analyzed several downstream target genes of Nodal signaling, *Nodal*, *Pitx2*, *Lefty1*, *Lefty2* and *Cer1* (Dickmeis et al., 2001; Katoh and Katoh, 2006; Whitman, 2001), in anterior and posterior explants. We found that 6 hours treatment with SB431542 reduced the expression of Nodal target genes efficiently in both anterior and posterior explants, but some residual expression of Nodal targets was observed in the posterior explants (Fig. 7D). This residual Nodal activity in the SB431542-treated posterior explants might be sufficient to allow differentiation into mesoderm/endoderm cells in the presence of BMP4.

In summary, our results suggest that attenuation of Nodal signaling during mouse gastrulation promotes initial formation of the ectodermal progenitor populations in the anterior region of the mouse embryo. Subsequent exposure to different levels of BMP signaling, based on their proximity to the ExE, could then determine the regional commitment to neural or epidermal fate.

DISCUSSION

The ectoderm, as defined by its potential to form neural and epidermal tissues, is essential for the formation of the central nervous system and the epidermis in the mouse embryo. However, unlike the mesoderm or endoderm, the exact domain of ectoderm potential is not clearly defined, and the mechanisms underlying its specification remain poorly understood. In this study, we aimed to address these questions through explant culture. We identified E7.0 as a key developmental stage when cells with potential to form neural and epidermal progenitors exist transiently in the anterior/proximal domain of the ectodermal layer. We further showed that brief attenuation of Nodal signaling promotes ectodermal formation and that subsequent exposure to BMP can determine epidermal versus neural fate in ectodermal explant cultures.

Heterotopic transplantation experiments have demonstrated that epiblast cells in E6.5 mouse embryo are capable of changing their developmental fate dependent on their final location after

transplantation (Parameswaran and Tam, 1995; Tam and Zhou, 1996). Transplantation performed in E7.0-E7.5 embryos showed that the anterior ectoderm can give rise to neurectoderm when injected into the distal tip, but contributes preferentially to surface ectoderm when transplanted into the posterior/proximal region. This implied the possibility of an ectodermal progenitor population that can subsequently differentiate into the neural and surface ectoderm depending on its position in the embryo (Beddington, 1982). Up to now there have only been a few published studies that addressed the existence of a putative ectodermal population in the mouse embryo, such as the recent study by Cajal and colleagues (Cajal et al., 2012). They identified a small group of ectodermal cells positioned between proximal and distal regions in the anterior ectoderm at E7.0 in which single cells could contribute to both surface ectoderm and neural ectoderm during normal embryonic development. This work demonstrated that neural and non-neural lineages are not yet clonally separated at late gastrulation stage, and suggested that classical surface ectoderm and forebrain markers do not strictly define lineages at this stage.

We have been able to extend Cajal and colleagues' findings with our explant culture approach and demonstrated that the area of ectoderm with potential to generate both neural and surface ectoderm extends beyond the narrow strip bordering the proximal and distal region of the anterior ectoderm that is normally fated to do so. Our results suggest that the anterior/proximal region of the ectodermal layer in E7.0 [no allantoic bud (OB) and early allantoic bud (EB) stages] mouse embryo contains a transient cell population that can efficiently differentiate into epidermis or neural tissue depending on the local environmental cues (such as the presence or absence of BMP4). The restricted location of the cells in the intact embryo that show this mixed fate probably reflects the graded response in the epiblast to extra-embryonic secretion of BMP4. In explant cultures, we can provide elevated levels of BMP signaling to all cells and detect a broader responsive population with this dual potential.

In mouse embryos, Nodal signaling is important for primitive streak formation and mesoderm/endoderm development (Brennan et al., 2001; Conlon et al., 1994; Dunn et al., 2004; Zhou et al., 1993). The AVE produces Nodal antagonists Lefty1 and cerberus 1 (Cer1) to block mesoderm formation in the anterior region and promote

neural development (Perea-Gomez et al., 2001; Perea-Gomez et al., 2002; Thomas and Beddington, 1996). Epiblast cells from $Nodal^{-/-}$ embryos readily differentiate into neurons in explant culture (Camus et al., 2006). Studies in mouse EpiSCs and human ESCs also revealed that inhibition of Nodal signaling promotes neural induction (Chng et al., 2010; Iwafuchi-Doi et al., 2012; Patani et al., 2009; Vallier et al., 2009).

Our data from E6.5 explant cultures suggest that transient Nodal inhibition can induce the formation of ectodermal progenitors with potential to form both neurectoderm and epidermis. Explant cultures of both anterior and posterior E6.5 ectoderm were able to upregulate mesoderm/endoderm markers in the presence of BMP4 (Fig. 2Ce,Cf). However, transient chemical inhibition of Nodal signaling in the anterior E6.5 explants reduced induction of mesoderm/endoderm markers, converting them into cells that are reminiscent of the anterior ectoderm at E7.0 (Fig. 7A).

The time window during which the anterior ectoderm cells can respond to the BMP4 signal is small. In the E7.0 mouse embryo, BMP4 signaling is active in the proximal region, as shown by the upregulation of the target genes $Id1$ and $Id2$ (Fig. 5A). As a result of the persistent activity of BMP signaling, perhaps in conjunction with other pathways, the ectoderm in the proximal region becomes committed to an epidermal fate at E7.5. By contrast, the absence of BMP4 and the presence of antagonists secreted by the node (McMahon et al., 1998; Tam and Behringer, 1997) direct the distal ectoderm to commit and differentiate into the neural lineage. This is reflected by the reduced capacity of the anterior/distal region of the E7.0 ectodermal layer to give rise to epidermal cells (Fig. 5Cb).

In summary, our explant culture experiments demonstrate the progression from pluripotency to transient ectodermal progenitors to neural and surface ectoderm lineage restriction in the anterior ectoderm germ layer from E6.5 to E7.5. This leads to the model (Fig. 8) that the anterior region of the early streak embryo, although initially pluripotent, gradually loses its mesoderm/endoderm potential in response to Nodal antagonists secreted from the adjacent AVE. This anterior population of cells with the capacity to form either surface ectoderm or neural cells is subsequently directed by a BMP signaling gradient along the proximal-distal axis to become committed to surface ectoderm or neurectoderm.
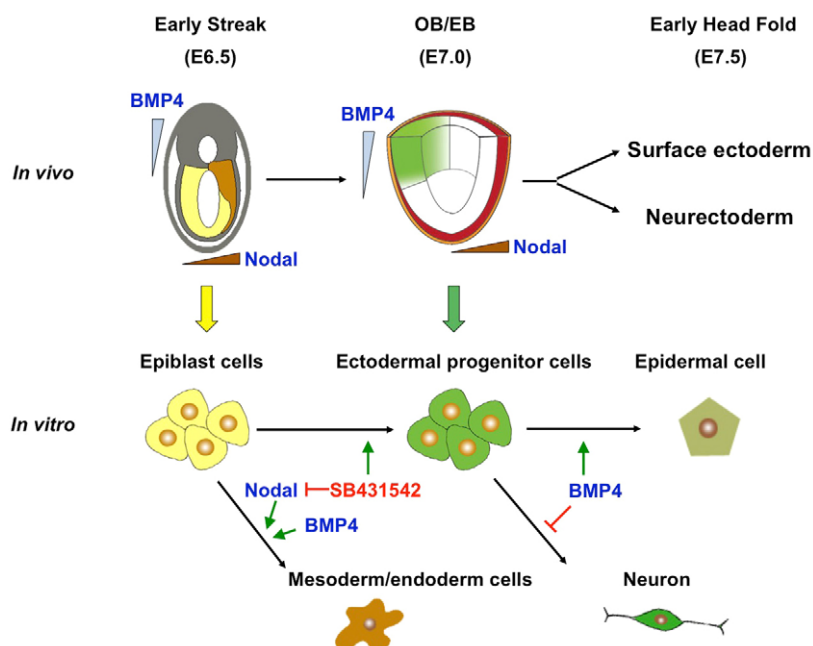

Fig. 8. Model for ectoderm formation during mouse embryonic development. The model shows the differentiation potential of the anterior ectoderm germ layer at different developmental stages. At early streak stage (E6.5), the anterior region of the epiblast is pluripotent. At OB/EB stages (E7.0), because of the low activity of Nodal signaling in the anterior side, the anterior/proximal ectoderm gradually loses its mesoderm/endoderm potential and becomes restricted to ectoderm with capacity to form either surface ectoderm (in the presence of BMP4) or neural cells (in the absence of BMP4). At early head fold stage (E7.5), the anterior ectoderm is subsequently directed by a BMP signaling gradient along the proximal-distal axis to become committed to surface ectoderm or neurectoderm.

It remains to be determined whether it is possible to isolate and maintain in culture a transient ectoderm population with the capacity to form both neurectoderm and surface ectoderm at the single-cell level. Our explant studies cannot exclude the possibility that individual cells within the potentially heterogeneous population are restricted to either neural or surface ectoderm. Additional studies will be required to demonstrate whether all cells of this transient ectoderm population possess bipotentiality to form neural and surface ectoderm *in vitro* and *in vivo*.

MATERIALS AND METHODS
Mouse embryo dissection
Mouse embryos were obtained from ICR outbred mice. The stages of the embryos were determined by dissection date and morphology (Downs and Davies, 1993; Lawson and Pedersen, 1987). We refer to early streak (ES) embryos as E6.5 mouse embryos, no allantoic bud (OB) and early allantoic bud (EB) embryos as E7.0 mouse embryos, and early head fold (EHF) embryos as E7.5 mouse embryos. For E6.5 mouse embryo dissection, embryos were incubated for 15 minutes at 4°C in cell dissociation buffer (CDB; Gibco) and then transferred to Ca^{2+}- and Mg^{2+}-free flushing and handling medium (Chemicon). Visceral endoderm was peeled away using the tip of 30 1/2-gauge needle, and the extra-embryonic ectoderm was cut off from the epiblast tissue. The epiblast tissue was then bisected into anterior and posterior parts. For E7.0 and E7.5 mouse embryo dissection, the whole embryo was first cut into anterior and posterior parts in CDB. Then, the mesodermal and endodermal layers were peeled away from the ectodermal layer using the tip of the needle.

Mouse embryo explant culture
After dissection, the isolated ectodermal layers were cultured in N2B27 medium in 96-well plates for up to 5 days. The N2B27 medium was composed of 50% DMEM/F12 (Gibco) and 50% Neurobasal (Gibco), supplemented with 1/200 (by volume) of N2 (2.5 mg/ml insulin, 10 mg/ml transferrin, 5 mg/ml bovine serum albumin, 2 μg/ml progesterone, 1.6 mg/ml putrescine, 3 nM selenite) and 1/100 (by volume) of B27 (Gibco) with 500 μM Glutamax (Gibco) and 100 μM β-mercaptoethanol (Gibco). The 96-well plates were pre-coated with fetal bovine serum and then washed twice in PBS before use. For Nodal inhibition assays from E6.5 explants, the anterior and posterior epiblast tissues were cultured with 10 μM SB431542 (Sigma) for 6 hours. For assessment of epidermal versus neurectodermal potential, the explants were cultured in N2B27 with or without BMP4 (10 ng/ml, R&D Systems, 314-BP-010) for 5 days.

Immunofluorescence analysis
Immunocytochemistry was performed as described previously (Gao et al., 2001). The following primary antibodies were used: mouse monoclonal anti-cytokeratin 18 (Krt18; also known as K18) (1:150; Abcam, ab668) and goat polyclonal anti-SOX1 (1:400, R&D systems, AF3369). Primary antibodies were detected with fluorescein isothiocyanate (FITC)- and Cy3-conjugated secondary antibodies (1:500; Jackson ImmunoResearch).

EGFP mouse and FACS
EGFP mouse embryos were ordered from Toronto Centre for Phenogenomics (TCP). Single-cell suspensions of co-cultured explants were obtained by dissociating with 0.05% trypsin at 37°C for 10 minutes. Flow cytometry was performed at the Sickkids - UHN Flow Cytometry Facility using a Becton Dickinson LSR II and Dako Cytomation MoFlo.

RNA preparation and quantitative PCR analysis
Total RNA was extracted from cells using Trizol reagent (Invitrogen), according to the manufacturer's instructions. Reverse transcription was performed with 0.1 μg of total RNA using SuperScript III reverse transcriptase (Invitrogen). Quantitative PCR was performed in accordance with the manufacturer's instructions, using Opticon Monitor (Eppendorf). Each sample was analyzed in triplicate, with the Ct values averaged and then normalized to *Gapdh* control. In each experiment, there were at least three

biological replicates. Each experiment was performed at least three times. Values shown on the graphs represent the mean value ± s.d. Student's *t*-tests were used to compare the effects of all treatments. Statistically significant differences are shown as follows: *$P<0.05$, **$P<0.01$. The primers are listed in supplementary material Table S1.

In situ hybridization
Whole-mount embryo *in situ* hybridization was performed as previously described (Yamanaka et al., 2007). The RNA probes used were: *Krt8* (from M. Llanos Casanova, Division of Epithelial Biomedicine, CIEMAT, Madrid, Spain), *Bmp4* (from Brigid Hogan, Department of Cell Biology, Duke University Medical Center, Durham, USA), *Id1* and *Id2* (Jen et al., 1996), *Pou5f1* (Kitamura et al., 2003), *T*, *Fgf5*, *Sox2*, *Oct6*, *Hesx1*, *Six3* and *K18* (*Krt18*) (PCR-amplified from cDNA). The primers are listed in supplementary material Table S2.

Author contributions
L.L. designed and performed the experiments, analyzed data and wrote the manuscript. C.L., S.B., Q.Z. and L.S. did in situ hybridization. F.L. contributed to experimental design. N.J. and J.R. supervised the project.

Supplementary material
Supplementary material available online at
http://dev.biologists.org/lookup/suppl/doi:10.1242/dev.092866/-/DC1

References
Aberdam, D., Gambaro, K., Medawar, A., Aberdam, E., Rostagno, P., de la Forest Divonne, S. and Rouleau, M. (2007a). Embryonic stem cells as a cellular model for neuroectodermal commitment and skin formation. *C. R. Biol.* **330**, 479-484.

Aberdam, D., Gambaro, K., Rostagno, P., Aberdam, E., de la Forest Divonne, S. and Rouleau, M. (2007b). Key role of p63 in BMP-4-induced epidermal commitment of embryonic stem cells. *Cell Cycle* **6**, 291-294.

Beddington, S. P. (1981). An autoradiographic analysis of the potency of embryonic ectoderm in the 8th day postimplantation mouse embryo. *J. Embryol. Exp. Morphol.* **64**, 87-104.

Beddington, R. S. (1982). An autoradiographic analysis of tissue potency in different regions of the embryonic ectoderm during gastrulation in the mouse. *J. Embryol. Exp. Morphol.* **69**, 265-285.

Brennan, J., Lu, C. C., Norris, D. P., Rodriguez, T. A., Beddington, R. S. and Robertson, E. J. (2001). Nodal signalling in the epiblast patterns the early mouse embryo. *Nature* **411**, 965-969.

Brons, I. G., Smithers, L. E., Trotter, M. W., Rugg-Gunn, P., Sun, B., Chuva de Sousa Lopes, S. M., Howlett, S. K., Clarkson, A., Ahrlund-Richter, L., Pedersen, R. A. et al. (2007). Derivation of pluripotent epiblast stem cells from mammalian embryos. *Nature* **448**, 191-195.

Cajal, M., Lawson, K. A., Hill, B., Moreau, A., Rao, J., Ross, A., Collignon, J. and Camus, A. (2012). Clonal and molecular analysis of the prospective anterior neural boundary in the mouse embryo. *Development* **139**, 423-436.

Camus, A., Perea-Gomez, A., Moreau, A. and Collignon, J. (2006). Absence of Nodal signaling promotes precocious neural differentiation in the mouse embryo. *Dev. Biol.* **295**, 743-755.

Chang, C. and Hemmati-Brivanlou, A. (1998). Cell fate determination in embryonic ectoderm. *J. Neurobiol.* **36**, 128-151.

Chng, Z., Teo, A., Pedersen, R. A. and Vallier, L. (2010). SIP1 mediates cell-fate decisions between neuroectoderm and mesendoderm in human pluripotent stem cells. *Cell Stem Cell* **6**, 59-70.

Conlon, F. L., Lyons, K. M., Takaesu, N., Barth, K. S., Kispert, A., Herrmann, B. and Robertson, E. J. (1994). A primary requirement for nodal in the formation and maintenance of the primitive streak in the mouse. *Development* **120**, 1919-1928.

Dickmeis, T., Aanstad, P., Clark, M., Fischer, N., Herwig, R., Mourrain, P., Blader, P., Rosa, F., Lehrach, H. and Strähle, U. (2001). Identification of nodal signaling targets by array analysis of induced complex probes. *Dev. Dyn.* **222**, 571-580.

Downs, K. M. and Davies, T. (1993). Staging of gastrulating mouse embryos by morphological landmarks in the dissecting microscope. *Development* **118**, 1255-1266.

Dunn, N. R., Vincent, S. D., Oxburgh, L., Robertson, E. J. and Bikoff, E. K. (2004). Combinatorial activities of Smad2 and Smad3 regulate mesoderm formation and patterning in the mouse embryo. *Development* **131**, 1717-1728.

Gao, X., Bian, W., Yang, J., Tang, K., Kitani, H., Atsumi, T. and Jing, N. (2001). A role of N-cadherin in neuronal differentiation of embryonic carcinoma P19 cells. *Biochem. Biophys. Res. Commun.* **284**, 1098-1103.

Hadjantonakis, A. K., Gertsenstein, M., Ikawa, M., Okabe, M. and Nagy, A. (1998). Generating green fluorescent mice by germline transmission of green fluorescent ES cells. *Mech. Dev.* **76**, 79-90.

Hart, A. H., Hartley, L., Sourris, K., Stadler, E. S., Li, R., Stanley, E. G., Tam, P. P., Elefanty, A. G. and Robb, L. (2002). Mixl1 is required for axial mesendoderm morphogenesis and patterning in the murine embryo. *Development* **129**, 3597-3608.

Hemmati-Brivanlou, A. and Melton, D. (1997a). Vertebrate embryonic cells will become nerve cells unless told otherwise. *Cell* **88**, 13-17.

Hemmati-Brivanlou, A. and Melton, D. (1997b). Vertebrate neural induction. *Annu. Rev. Neurosci.* **20**, 43-60.

Hendrickx, M., Van, X. H. and Leyns, L. (2009). Anterior-posterior patterning of neural differentiated embryonic stem cells by canonical Wnts, Fgfs, Bmp4 and their respective antagonists. *Dev. Growth Differ.* **51**, 687-698.

Inman, G. J., Nicolás, F. J., Callahan, J. F., Harling, J. D., Gaster, L. M., Reith, A. D., Laping, N. J. and Hill, C. S. (2002). SB-431542 is a potent and specific inhibitor of transforming growth factor-beta superfamily type I activin receptor-like kinase (ALK) receptors ALK4, ALK5, and ALK7. *Mol. Pharmacol.* **62**, 65-74.

Iwafuchi-Doi, M., Matsuda, K., Murakami, K., Niwa, H., Tesar, P. J., Aruga, J., Matsuo, I. and Kondoh, H. (2012). Transcriptional regulatory networks in epiblast cells and during anterior neural plate development as modeled in epiblast stem cells. *Development* **139**, 3926-3937.

Jen, Y., Manova, K. and Benezra, R. (1996). Expression patterns of Id1, Id2, and Id3 are highly related but distinct from that of Id4 during mouse embryogenesis. *Dev. Dyn.* **207**, 235-252.

Katoh, M. and Katoh, M. (2006). CER1 is a common target of WNT and NODAL signaling pathways in human embryonic stem cells. *Int. J. Mol. Med.* **17**, 795-799.

Kirfel, J., Magin, T. M. and Reichelt, J. (2003). Keratins: a structural scaffold with emerging functions. *Cell. Mol. Life Sci.* **60**, 56-71.

Kitamura, T., Koshino, Y., Shibata, F., Oki, T., Nakajima, H., Nosaka, T. and Kumagai, H. (2003). Retrovirus-mediated gene transfer and expression cloning: powerful tools in functional genomics. *Exp. Hematol.* **31**, 1007-1014.

Laping, N. J., Grygielko, E., Mathur, A., Butter, S., Bomberger, J., Tweed, C., Martin, W., Fornwald, J., Lehr, R., Harling, J. et al. (2002). Inhibition of transforming growth factor (TGF)-beta1-induced extracellular matrix with a novel inhibitor of the TGF-beta type I receptor kinase activity: SB-431542. *Mol. Pharmacol.* **62**, 58-64.

Lawson, K. A. and Pedersen, R. A. (1987). Cell fate, morphogenetic movement and population kinetics of embryonic endoderm at the time of germ layer formation in the mouse. *Development* **101**, 627-652.

Lawson, K. A., Meneses, J. J. and Pedersen, R. A. (1991). Clonal analysis of epiblast fate during germ layer formation in the mouse embryo. *Development* **113**, 891-911.

Lu, C. C., Brennan, J. and Robertson, E. J. (2001). From fertilization to gastrulation: axis formation in the mouse embryo. *Curr. Opin. Genet. Dev.* **11**, 384-392.

McMahon, J. A., Takada, S., Zimmerman, L. B., Fan, C. M., Harland, R. M. and McMahon, A. P. (1998). Noggin-mediated antagonism of BMP signaling is required for growth and patterning of the neural tube and somite. *Genes Dev.* **12**, 1438-1452.

Moll, R., Franke, W. W., Schiller, D. L., Geiger, B. and Krepler, R. (1982). The catalog of human cytokeratins: patterns of expression in normal epithelia, tumors and cultured cells. *Cell* **31**, 11-24.

Moon, B. S., Yoon, J. Y., Kim, M. Y., Lee, S. H., Choi, T. and Choi, K. Y. (2009). Bone morphogenetic protein 4 stimulates neuronal differentiation of neuronal stem cells through the ERK pathway. *Exp. Mol. Med.* **41**, 116-125.

Oliver, G., Mailhos, A., Wehr, R., Copeland, N. G., Jenkins, N. A. and Gruss, P. (1995). Six3, a murine homologue of the sine oculis gene, demarcates the most anterior border of the developing neural plate and is expressed during eye development. *Development* **121**, 4045-4055.

Osorno, R., Tsakiridis, A., Wong, F., Cambray, N., Economou, C., Wilkie, R., Blin, G., Scotting, P. J., Chambers, I. and Wilson, V. (2012). The developmental dismantling of pluripotency is reversed by ectopic Oct4 expression. *Development* **139**, 2288-2298.

Parameswaran, M. and Tam, P. P. (1995). Regionalisation of cell fate and morphogenetic movement of the mesoderm during mouse gastrulation. *Dev. Genet.* **17**, 16-28.

Patani, R., Compston, A., Puddifoot, C. A., Wyllie, D. J., Hardingham, G. E., Allen, N. D. and Chandran, S. (2009). Activin/Nodal inhibition alone accelerates highly efficient neural conversion from human embryonic stem cells and imposes a caudal positional identity. *PLoS ONE* **4**, e7327.

Perea-Gomez, A., Lawson, K. A., Rhinn, M., Zakin, L., Brûlet, P., Mazan, S. and Ang, S. L. (2001). Otx2 is required for visceral endoderm movement and for the restriction of posterior signals in the epiblast of the mouse embryo. *Development* **128**, 753-765.

Perea-Gomez, A., Vella, F. D., Shawlot, W., Oulad-Abdelghani, M., Chazaud, C., Meno, C., Pfister, V., Chen, L., Robertson, E., Hamada, H. et al. (2002). Nodal antagonists in the anterior visceral endoderm prevent the formation of multiple primitive streaks. *Dev. Cell* **3**, 745-756.

Quinlan, G. A., Williams, E. A., Tan, S. S. and Tam, P. P. (1995). Neuroectodermal fate of epiblast cells in the distal region of the mouse egg cylinder: implication for body plan organization during early embryogenesis. *Development* **121**, 87-98.

Shan, Z. Y., Liu, F., Lei, L., Li, Q. M., Jin, L. H., Wu, Y. S., Li, X. and Shen, J. L. (2011). Generation of dorsal spinal cord GABAergic neurons from mouse embryonic stem cells. *Cell Reprogram* **13**, 85-91.

Tam, P. P. (1989). Regionalisation of the mouse embryonic ectoderm: allocation of prospective ectodermal tissues during gastrulation. *Development* **107**, 55-67.

Tam, P. P. and Behringer, R. R. (1997). Mouse gastrulation: the formation of a mammalian body plan. *Mech. Dev.* **68**, 3-25.

Tam, P. P. and Loebel, D. A. (2007). Gene function in mouse embryogenesis: get set for gastrulation. *Nat. Rev. Genet.* **8**, 368-381.

Tam, P. P. and Quinlan, G. A. (1996). Mapping vertebrate embryos. *Curr. Biol.* **6**, 104-106.

Tam, P. P. and Zhou, S. X. (1996). The allocation of epiblast cells to ectodermal and germ-line lineages is influenced by the position of the cells in the gastrulating mouse embryo. *Dev. Biol.* **178**, 124-132.

Tesar, P. J., Chenoweth, J. G., Brook, F. A., Davies, T. J., Evans, E. P., Mack, D. L., Gardner, R. L. and McKay, R. D. (2007). New cell lines from mouse epiblast share defining features with human embryonic stem cells. *Nature* **448**, 196-199.

Thomas, P. and Beddington, R. (1996). Anterior primitive endoderm may be responsible for patterning the anterior neural plate in the mouse embryo. *Curr. Biol.* **6**, 1487-1496.

Thomas, P. Q., Brown, A. and Beddington, R. S. (1998). Hex: a homeobox gene revealing peri-implantation asymmetry in the mouse embryo and an early transient marker of endothelial cell precursors. *Development* **125**, 85-94.

Troy, T. C., Arabzadeh, A. and Turksen, K. (2011). Re-assessing K15 as an epidermal stem cell marker. *Stem Cell Rev.* **7**, 927-934.

Vallier, L., Touboul, T., Chng, Z., Brimpari, M., Hannan, N., Millan, E., Smithers, L. E., Trotter, M., Rugg-Gunn, P., Weber, A. et al. (2009). Early cell fate decisions of human embryonic stem cells and mouse epiblast stem cells are controlled by the same signalling pathways. *PLoS ONE* **4**, e6082.

Whitman, M. (2001). Nodal signaling in early vertebrate embryos: themes and variations. *Dev. Cell* **1**, 605-617.

Wilson, P. A. and Hemmati-Brivanlou, A. (1995). Induction of epidermis and inhibition of neural fate by Bmp-4. *Nature* **376**, 331-333.

Yamaguchi, T. P., Dumont, D. J., Conlon, R. A., Breitman, M. L. and Rossant, J. (1993). flk-1, an flt-related receptor tyrosine kinase is an early marker for endothelial cell precursors. *Development* **118**, 489-498.

Yamanaka, Y., Tamplin, O. J., Beckers, A., Gossler, A. and Rossant, J. (2007). Live imaging and genetic analysis of mouse notochord formation reveals regional morphogenetic mechanisms. *Dev. Cell* **13**, 884-896.

Yasunaga, M., Tada, S., Torikai-Nishikawa, S., Nakano, Y., Okada, M., Jakt, L. M., Nishikawa, S., Chiba, T., Era, T. and Nishikawa, S. (2005). Induction and monitoring of definitive and visceral endoderm differentiation of mouse ES cells. *Nat. Biotechnol.* **23**, 1542-1550.

Zhou, X., Sasaki, H., Lowe, L., Hogan, B. L. and Kuehn, M. R. (1993). Nodal is a novel TGF-beta-like gene expressed in the mouse node during gastrulation. *Nature* **361**, 543-547.